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NONLINEAR LOW FREQUENCY (LF) COMETARY WAVES:

Bruce 'T'. Tsurutani
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91109

ABSTRACT

The study of nonlinear plasma waves is an emerging field in plasma physics. One advantage of research in Space plasmas is that we can make detailed in situ measurements of Low Frequency waves and study the evolution of their nonlinear properties, a technique that is not possible for higher frequency waves typically of laboratory plasmas. This paper will present a review of nonlinear properties of LF waves at comets.

INTRODUCTION

The nonlinear features of Low Frequency (LF) magnetosonic waves detected at comet Giacobini-Zinner will be illustrated and discussed. It should be noted that this (discussion will cover only a small fraction of the wave modes detected at comets. For a comprehensive review of the literature for all waves (including the magnetosonic mode), it is recommended that one start with the seminal Wu and Davidson (1972) article., and then follow up with a series of articles and review articles: Gary (1991), Brinca (1991), Tsurutani (1991) and Roberts and Goldstein (1991).

In this paper, I will start with a brief description of the resonant instability and the sources of free energy for the waves. This topic is well understood and is provided for background material. The heart of the paper is the nonlinear properties of the waves. These phenomena will be discussed in the order of their temporal development. First, simple steepened magnetosonic waves and their basic features will be discussed. As the wave steepens further, large amplitude whistler packets are formed. I'll discuss the properties of the whistlers and their potential generation mechanism(s) will be covered next. A discussion of fully developed magnetosonic waves will follow. These waves have regions of phase rotations within a single magnetosonic wave, wave splitting into two "halves" and "back" rotations or rotations of the opposite sense. Power spectra of the waves will be illustrated with a (discussion of whether the cometary waves are really a form of turbulence or not. Potential (cascade?) processes will be discussed with a statement of our present understanding of the physical mechanisms.

RESULTS

A. Magnetosonic Wave Generation: Comets

An overview of the wave “turbulence” observed near Comet Giacobini-Zinner is illustrated in Fig. 1, taken from Smith *et al.* (1986) and Tsurutani and Smith (1986a). From top to bottom, the three panels illustrate the field magnitude and the elevation and the azimuthal angles, the latter two in GSE coordinates. Closest approach to the nucleus occurred at ~ 1103 UT, at a distance of ~ 7800 km in the antisunward direction. Several cometary features are indicated in the Fig. for reference. The magnetic tail lobes have dimensions of $\sim 10,000$ km. The distance to the bow wave/shock is $\sim 100,000$ km. The “turbulence” or fluctuations in magnetic field directionality exists throughout the data on this plot ($\sim \pm 200,000$ km) and extends to at least $\sim \pm 1,000,000$ km (Tsurutani and Smith, 1986a).

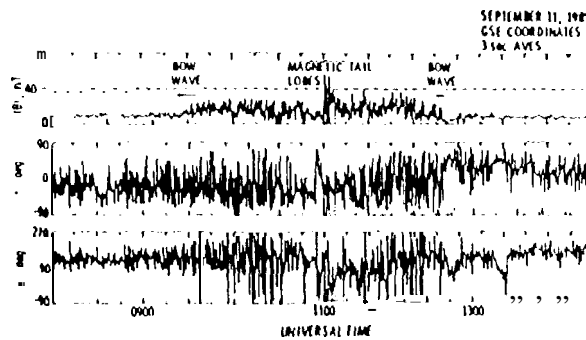


Figure 1. An overview of the Comet Giacobini-Zinner wave “turbulence”.

The topic of this review article is the properties of the large amplitude nonlinear fluctuations shown in the Fig. Because the cometary ion pickup instability is strongly driven, and because the frequency of the waves is low (114 ion group gyrofrequencies), scientists have been able to identify fundamental nonlinear features using tic. magnetometers.

Note that the “turbulence”, as denoted by the fluctuations in the polar and azimuthal angles, δ and ϕ , are not influenced by the presence of the broad bow wave/shock near ~ 0930 UT. The fluctuations have essentially the same amplitudes before (upstream) and after (downstream) of ~ 0930 UT. There is a decrease in wave amplitude on the outbound leg, however. This may in part be due to a substantial and abrupt shift in the direction of the interplanetary (IMF) magnetic field direction several minutes prior to the crossing of the bow wave/shock. Wave growth rates are dependent on the IMF angle relative to the solar wind velocity (Torber and Tsurutani, 1987; Brinca and Tsurutani, 1988; Gary and Madland, 1988); this angular change may be the cause of the sudden wave amplitude decrease.

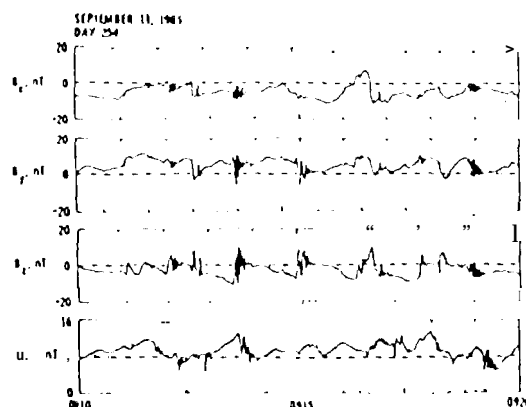


Figure 2. An example of the steepened magnetosonic waves with attached whistler precursors. Taken from Tsurutani *et al.* (1987).

A higher time resolution examination of the waves is available in Fig. 2. This data illustrates that the field fluctuations are not random, but that the fluctuations in the components are correlated, indicating that there are discrete wave modes present. Two important features which I will focus on in this review are the ~100s magnetosonic mode waves (best seen in the sawtooth pattern in B_z) and the high frequency (~3 Hz) whistler packets at the ends of the magnetosonic waves. The latter can be noted at -0913:40 UT, -0915:00 UT and elsewhere in the Fig.

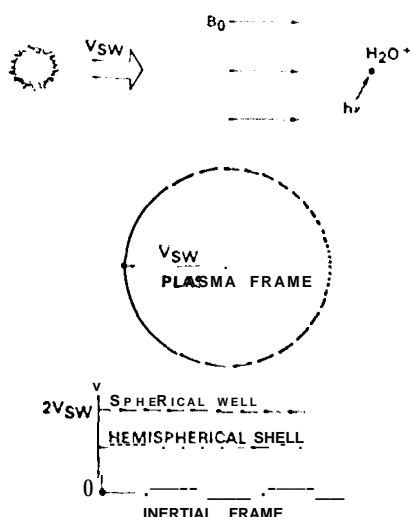


Figure 3. A schematic of the pickup of cometary ions when V_{SW} is parallel to the IMF B . The ions form a beam in velocity space.

The source of free energy for the instability and the waves is schematically illustrated in Fig. 3. As the comet approaches the sun, solar heating causes the atoms and molecules of the nucleus to sublimate from the surface. The outward radial propagation of the neutral atoms and molecules is approximately 1 km/s. The combined photoionization and the charge exchange time scale is ~10⁶ s. Thus, the atoms/molecules travel approximately 10⁶ km before being ionized. It is believed that ~80% of the nucleus is composed of water ice, so the predominant ion is from the H₂O group (H₂O⁺, OH⁺ and O⁺).

When water molecules (or OH or O) are ionized, as shown in Fig. 3, they form a beam in the solar wind plasma frame with velocity $-V_{sw}$, where V_{sw} is the solar wind velocity. (There is a small velocity of the comet nucleus relative to the sun and an even smaller velocity of the cometary neutrals relative to the nucleus, but these can be neglected in this simple picture). This beam is unstable to the right-hand resonant ion beam instability (WU and Davidson, 1972; Brinca, 1991, and references therein). In this instability, the ions are traveling towards the sun in the plasma frame and are overtaking the right-hand (magnetosonic) waves which are also propagating in the general direction of the sun. Because the (left-hand) ions overtake the waves, they sense the waves as left-hand polarized, allowing an anomalous Doppler-shifted resonant interaction to occur. The predominant wave-particle interaction is pitch angle scattering, leading to the formation of a spherical shell in velocity space, as schematically indicated in Fig. 3.

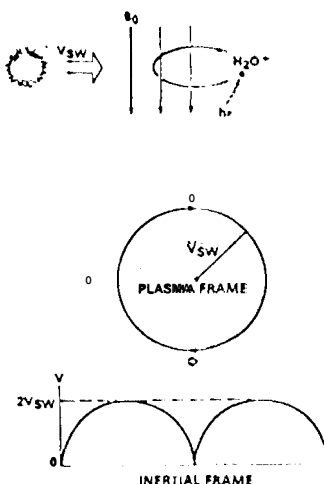


Figure 4. A schematic of the pickup of cometary ions when V_{sw} is perpendicular to the IMF B . The ions form a ring in velocity space.

These right-hand magnetosonic waves propagate at $\sim 2-3$ times the Alfvén speed due to their steepened features (Omidi and Winske, 1987). The velocities are still substantially less than the solar wind speed ($V_{sw} \cong 7-10$ VA), however. The waves are therefore blown back across the spacecraft by the solar wind and are observed with the leading steepened edge of the magnetosonic waves occurring last in time (see Fig. 2).

When the IMF is not parallel to V_{sw} , there are substantial forces exerted on the ions, leading to instantaneous acceleration and "pick-up" of the particles. The extreme case of $\alpha = 90^\circ$ is illustrated in Fig. 4. The solar wind $V \times B$ Lorentz force causes the H_2O group ions to form a ring in phase space. The ions will have a gyrovelocity V_{sw} in the solar wind plasma frame. Thus, in the comet frame, the ions have maximum and minimum speeds of $2V_{sw}$ and 0, respectively. Because the spacecraft is essentially in the cometary frame (there is a 21 km S-I relative velocity for ICE at Giacobini-Zinner), energetic ion detectors have directly observed these thermally "cold" pickup ions (the ion temperature refers to their transverse and parallel velocity fluctuations). The maximum kinetic energy of the ring is about 60 keV.

Although the interplanetary magnetic field is usually at the Parker spiral angle relative to the solar wind ($\sim 45^\circ$ at 1 AU), it can exist at all angles from a parallel orientation as schematically shown in Fig. 3, to a perpendicular orientation shown in Fig. 4. The right-hand resonant instability has positive growth for angles from 0° to $\sim 70^\circ$ (Brinca, 1991). For angles closer to 90° the dominant instability should be the left-hand resonant mode or the mirror mode (Brinca, 1991). However, a search for the left hand mode (the mode with the theoretically largest growth rate) has indicated a lack of the presence of such waves near comets even under the proper ($\alpha \equiv 70^\circ$ – 90°) conditions (Tsurutani *et al.*, 1989a). The authors suggested several possible explanations for the suppression of this instability, but tests have not been made to date.

One feature of the cometary waves which has made analyses quite easy, is that the spacecraft is essentially in the same reference frame as the cometary neutrals, and thus the spaceborne magnetometers detect the waves in essentially the ion reference frame. The ~ 100 s wave period corresponds to the H_2O group ion cyclotron frequency.

C. Off-Axis Wave Propagation

There are several fundamental theoretical problems with several of the above wave features that should be noted by the reader. Linear and quasilinear theory (Thorne and Tsurutani, 1987; Brinca and Tsurutani, 1988; Gary and Madland, 1988) indicate that maximum growth should occur at $\theta_{\mathbf{k}\mathbf{B}} = 0^\circ$. However, the observed steepened cometary waves are found to be propagating at substantial angles to the ambient magnetic field direction, consistent with their steepened properties.

Even at very large distances from the comet nucleus where the wave amplitudes and density variations are small, the waves are still found to propagate at large angles to \mathbf{B} and show signs of substantial steepening. Researchers have not found noncompressive, parallel propagating waves in any location near a comet. One possible explanation to this dilemma is that nonlinear saturation is causing a limitation in the growth of the parallel propagating waves, allowing the off-axis waves to dominate (Kojima *et al.*, 1989). Although preliminary results have been orally presented, further work is needed on this topic.

D. Nonlinear Wave Development

Waves detected at intermediate distances from the comet typically have some steepening, but generally have a lack of whistler precursors. An example is given in Figs. 5 and 6, observed at a distance $\sim 2.1 \times 10^5$ km from the comet. Sixty seconds of the wave is displayed. From the beginning of the interval at 0718:20 UT until point 1, there is little phase rotation present. This is best seen in the hodogram plot of Fig. 6. This part of the wave is linearly polarized and is almost purely compressive. In this interval, B_1 and B_2 are nearly constant with almost all of the change occurring in B_3 , the direction of minimum variance (along \mathbf{B}). The majority of the wave phase rotation occurs in the last 10s of the wave, from point 1 to point 4. This wave is reasonably planar.

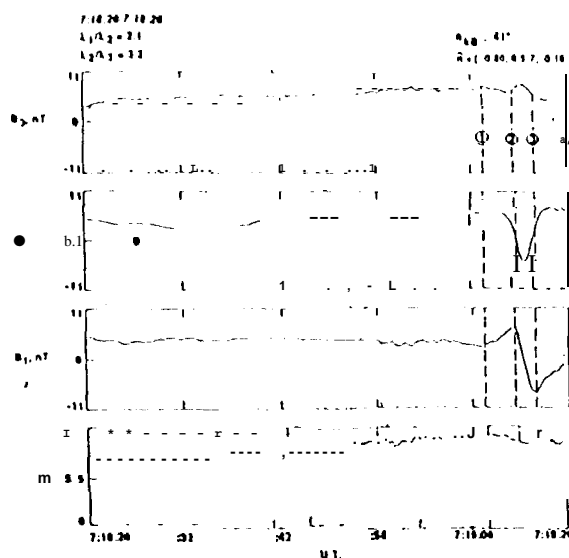


Figure 5. An example of a simple steepened magnetosonic wave without a whistler precursor.

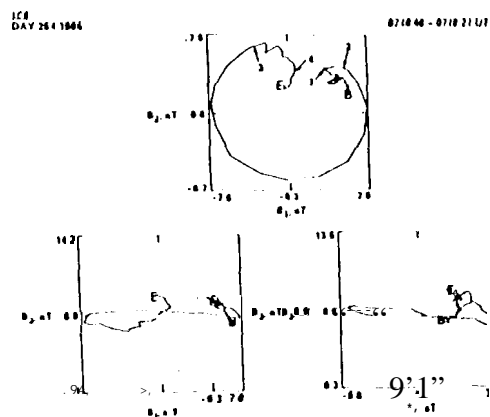


Figure 6. A hodogram of the wave in Fig. 5.

The general picture for wave steepening is illustrated in Fig. 7, an adaptation from Cohen and Kulsrud (1975). The wave originally starts as a sinusoidal oscillation (top panel), traveling to the left. Points of equal phase separation are indicated in the vertical scale. As the wave steepens it forms a front where much of the phase rotation accumulates. The phase change is highly compressed, and corresponds to the “partial rotation”, shown previously. The trailing portion of the wave is elongated, containing the remainder (- quarter) of the wave phase rotation. This region corresponds to the “linear” portion of the wave. Note that in the process of wave steepening, the wave has evolved from a monochromatic oscillation to one which consists of a broad range of frequencies. “The leading edge of the magnetosonic wave

corresponds to frequencies higher than the $f_{H_2O^+}$ gyrofrequency and the trailing portion to frequencies lower than the $f_{H_2O^+}$ gyrofrequency.

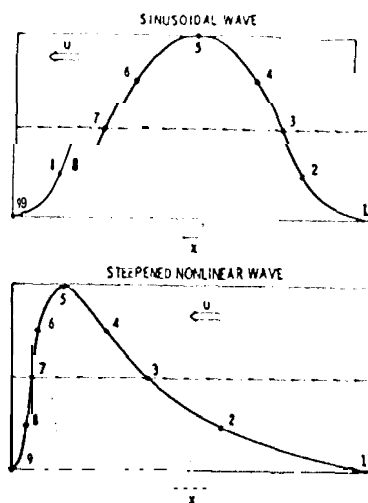


Figure 7. A simplified schematic for magnetosonic wave steepening, adapted from Cohen and Kulsrud (1975).

F. Whistler Packets

The fully developed whistler packets have a different field rotation than the partial rotation. An example of a whistler packet is shown in Fig. 8, taken during an interval much closer to the comet nucleus ($\sim 1.3 \times 10^5$ km). The whistler decreases in amplitude linearly with distance from the magnetosonic wave. The field spirals around the upstream ambient direction until it ends at B. The whistler acts to lower the field gradient across the steepened magnetosonic wave front, allowing a more gradual field reduction by the spiral motion. In this particular event, the whistler is a planar structure.

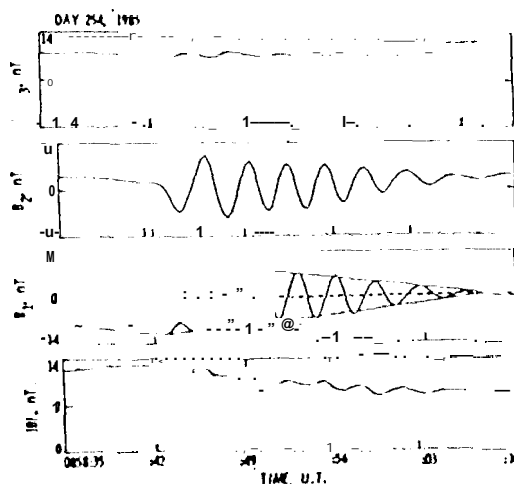


Figure 8. An example of a whistler precursor. Taken from Tsurutani *et al.* (1989b).

A number of different statistical properties of the whistlers were given in Tsurutani *et al.* (1989b). The only scatter plot that illustrated any significant correlation is shown in Fig. 9. It is a plot of the average period of the whistlers in spacecraft coordinates versus the number of rotations in the packet. It is found that, in general, packets with large numbers of rotations have smaller wave periods and vice versa. Note that in this examination, the whistler direction of propagation relationship, higher frequency waves propagate at higher phase velocities. Since

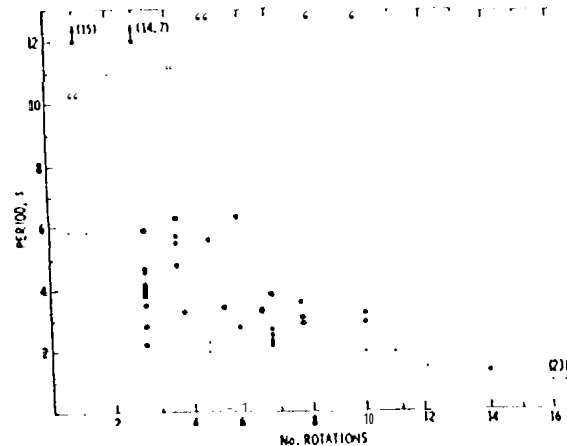


Figure 9. The whistler wave average period as a function of the number of wave cycles in the whistler packet. Taken from Tsurutani *et al.* (1989b).

the waves are propagating in the solar direction (in the opposite direction to the solar wind), relatively higher frequency waves will have smaller anomalous Doppler shifts. Thus the actual distributional dependence is probably more extreme than in the given plot.

One interesting feature of the statistics in Fig. 9 is that the whistler packet physical scale length increases on average with increasing number of cycles. An event with only one cycle (partial rotation) may have a period of ~ 10 s. Assuming a solar wind velocity of 400 km s^{-1} , one gets a scale size of $4 \times 10^3 \text{ km}$. The observed whistler packet with the greatest number of rotations (23) had an average period of ~ 1.0 s, giving a train length of $\sim 9.2 \times 10^3 \text{ km}$. The latter is slightly more than double the length of the partial rotation. This observation should be taken into account in any theory of the formation of the steepened waves plus whistler packets.

There have been several suggested mechanisms for the whistler packet. Among them are dispersive whistlers, generated by the wave steepening process (Hada *et al.*, 1987; Omidi and Winske, 1990), pickup of H_2O group ions at the leading steepened edge of the magnetosonic waves (Goldstein and Wong, 1987), pickup of cometary protons at the leading steepened edge (Brinca and Tsurutani, 1988b), and trapping of H_2O group ions in the whistler packet (Kaya *et al.*, 1989). All of these mechanisms are viable. The fundamental question is what is the relative contributions of each mechanism. Recently Omidi and Winske (1990) indicated that the whistler amplitude is only slightly enhanced if fresh pickup ions are added to the simulation in comparison to the case where no new ions are added. This result implies that the dominant process is dispersive whistler generation from the nonlinear steepening process. However, contributions from other sources may certainly be present and important.

G. Fully Developed LF Waves

Figs.10 and 11 illustrate a fully developed magnetosonic wave with upstream whistlers. One feature to note is the unusually large amplitude whistler packet (pak-to-peak amplitudes of ~ 10 nT), which at this stage of development have very little fall-off in amplitude with distance. The whistlers are also highly compressional, as denoted in the B magnitude panel. Besides the whistler packet (left-handed in the spacecraft frame), there is one other small region of left-hand rotation in the magnetosonic wave, from points 3 to 4. In addition to the two regions of phase rotation, there are two more regions of the magnetosonic wave which are almost purely compressional (with almost no phase rotation). One is the trailing - half of the wave from the beginning of the interval from 0826:08 UT.

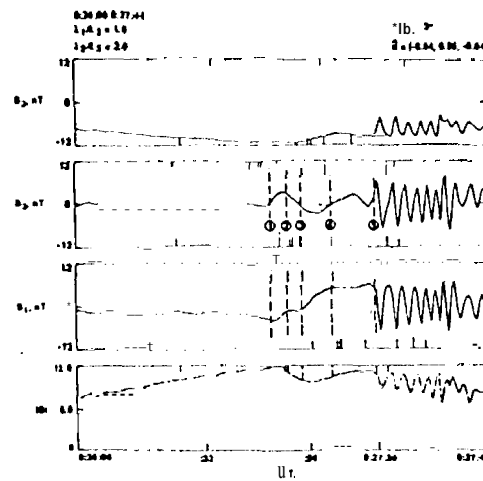


Figure 10. A fully developed magnetosonic wave with upstream whistlers. Taken from Tsurutani *et al.* (1990).

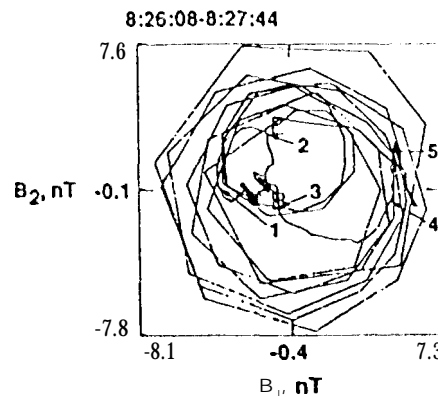


Figure 11. The hodograms for the wave in Fig. 10.

One of the two most striking features of the wave in Fig. 10 are found between points 1 and 3. The field rotation in this region corresponds to a full 360° right-hand rotation in the spacecraft frame. This is opposite in sense to that of the partial rotation or of the upstream whistlers. This dramatic feature can easily be noticed in Fig. 11. At present it is not known what this feature is. One possibility is that it is a right-hand wave (in the plasma frame) traveling in the downstream direction away from the sun. Such a wave could be generated by the decay instability stimulated by the interaction of a whistler (the dispersive whistlers) with acoustic waves (or density compressions associated with the, magnetosonic or whistler waves propagating at nonzero angles to B). It could also be a left-hand wave propagating into the upstream direction. With triaxial magnetic measurements, there is an ambiguity of 180° in the direction of k , thus one cannot determine the absolute direction of propagation without using additional physical arguments or high time resolution velocity measurements (the latter unfortunately do not exist on ICE). A third possibility is that it could be a backward propagating dispersive whistler generated by the steepening process.

This "back" rotation is also correlated with a second interesting feature located near point 3 of Fig. 10. At and near that portion of the wave, it appears as if the wave is splitting into two parts. It is unclear whether the rotation is related to this feature or not at this time. Back rotations occur less than ~ 10% of the time. The wave splittings also occur with approximately the same frequency.

H. Comet Halley Waves

One fundamental question that many people have asked (but have not had answered), is "why were the fields measured by spacecraft armada at comet Halley more turbulent looking (but lower in amplitude) than the nicely periodic structures observed at Giacobini-Zinner?". The scale size of Halley's interaction with the solar wind was an order of magnitude larger than that for comet Giacobini-Zinner. This is caused by the larger neutral production of Halley. The bow shock/wave was detected at ~ 10^6 km for Halley versus ~ 10^5 km for Giacobini-Zinner. The detection of cometary ions was found for distances up to 8×10^6 km versus 2×10^6 km for Halley and Giacobini-Zinner, respectively. The reason is the much greater ion production rate of Halley, roughly 15 times that of Giacobini-Zinner. The waves generated by the pickup process will similarly have an order of magnitude greater time to expand and interact with each other. Thus, the turbulent nature of the fields measured near Halley (Glassmeier *et al.* 1987; Johnstone *et al.*, 1987) may be the eventual by-products of wave-wave interactions. At this time, this conjecture can only remain as speculation, or could be tested by simulation analyses.

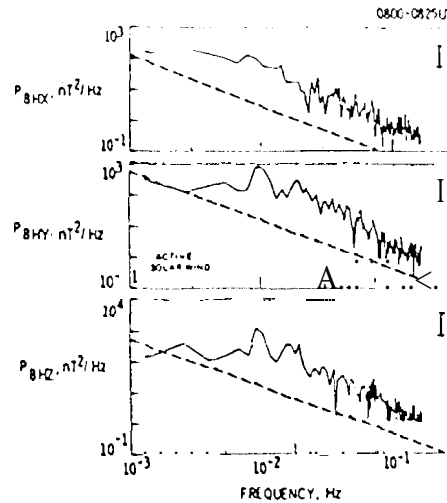


Figure 12. The power spectra of the waves just upstream of the Giacobini-Zinner bow shock/wave on the inbound pass. The figure is taken from Tsurutani and Smith [11].

The power spectra of the field just upstream of the Giacobini-Zinner bow shock is shown in Fig.12. The X component is along the average magnetic field direction and Y and Z are in the orthogonal directions. Originally, this author (Tsurutani and Smith, 1986a) and several Giotto magnetometer investigators (Acuna *et al.*, 1986; Glassmeier *et al.*, 1987) speculated that the $f^{-5/3}$ to f^{-2} power law spectra of the waves at frequencies higher than the pump (H_2O group ion gyrofrequency) could be due to an inverse cascade. An assumption was made that the cause of the wave spectra from the two comets were the same. However, this may not be correct. After the previous discussion, two points come to mind. First, it has been shown that the dominant components of the Giacobini-Zinner waves in this frequency range are right-hand polarized in the plasma frame. Presumably, all of this power is due to the steepened magnetosonic waves, partial rotations and the Whistlers, in order of ascending frequency. The amount of power in the “back” rotations should be small. The waves at Halley have been noted to be quite different from comet Giacobini-Zinner (Glassmeier *et al.*, 1987; 1989; Johnstone *et al.* 1987). These waves may indeed be turbulence due to a nonlinear evolution of the pump waves or by further wave-wave interactions (previously discussed). Thus the comet Halley spectrum may not be composed of solely whistlers and these waves may be quite different than those of G-Z. It is felt that several new studies are called for: from cross spectra] analyses, 1) a study of the helicity of the waves at G-Z and Halley, both upstream and downstream of the bow shock/wave, 2) a study of the spectral and polarization evolution of the Halley waves far from the comet to close to the comet nucleus, and from plasma and magnetic field (diagnostics. 3) the compressibility and Alfvén ratio.

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